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Novel Research Into the Impacts of Ocean Acidification Upon Tropical Tuna

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Introduction

Experimental trials were recently conducted at the Inter-American Tropical Tuna Commission (IATTC) Achotines Laboratory in Panama to investigate the potential impacts of ocean acidification on the early life history stages of *Thunnus albacares* (yellowfin tuna). With analyses of data collected from the trials expected to be completed soon, the following article describes the growing need for such research and provides an overview of the project, including a description of the recently conducted trials.

Background

Anthropogenic (man-made) carbon dioxide (CO_2) emissions are resulting in increasing concentrations of CO_2 in the earth's atmosphere (IPCC 2007). This buildup in atmospheric CO_2 is, in turn, causing a gradual warming and acidification of the earth's oceans (e.g., Barnett et al. 2005, Caldeira and Wickett 2003, Feely et al. 2004). Both warming and acidification have the potential to affect the distribution and population dynamics of many marine organisms (IPCC 2007, Raven et al. 2005, Fabry et al. 2008). Tuna populations are key components of pelagic ecosystems and, in the Pacific Ocean, form the basis of one of the largest and most valuable fisheries in the world (Williams and Terawasi 2009). While tuna scientists are now attempting to predict how ocean warming will affect Pacific tuna populations (Lehodey et al. 2010), no one has previously investigated how ocean acidification may affect these species and associated fisheries.

To understand why ocean acidification might be a concern for tuna and other marine organisms we need to understand a little about the process itself. Concentrations of CO_2 in the ocean tend towards equilibrium with the CO_2 in the atmosphere. To date, the world's oceans have absorbed

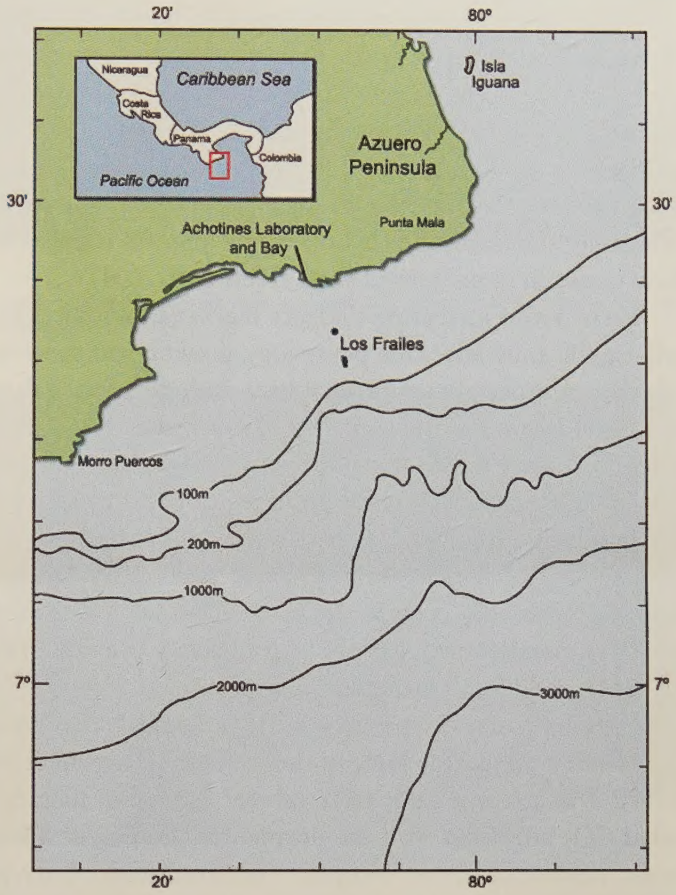

Figure 1. Achotines Bay location

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about 30%–50% of global man-made CO_2 emissions (Feely et al. 2004, Sabine et al. 2004, Orr et al. 2005). This has substantially changed ocean water chemistry—specifically by increasing concentrations of dissolved CO_2 (aq), H_2CO_3 (carbonic acid), HCO_3^- (bicarbonate ions), and H^+ (hydrogen ions), and decreasing concentrations of CO_3^{2-} (carbonate ions; Fabry et al. 2008).

Increased concentrations of oceanic CO_2 have lowered the average sea-surface pH by 0.1 units (i.e., making the ocean more acidic and less alkaline) since the start of the industrial revolution. It is projected that uptake of atmospheric CO_2 by global oceans will further reduce sea-surface pH by 0.3–0.4 units by 2100 (Caldeira and Wicket 2003, 2005). These represent larger and faster shifts in oceanic pH than any thought to have occurred in millions of years (Feely et al. 2004).

There is now increasing evidence that ocean acidification will significantly affect the physiology, growth, and survival of a diverse range of marine organisms, including fish (Fabry et al. 2008, Guinotte and Fabry 2008, Raven et al. 2005). The early life history stages of a number of fish species are sensitive to the elevated CO_2 levels projected to occur by the end of this century. Studies have found negative impacts on larval behavior and sensory capacity (Dominici et al. 2012, Devine et al. 2012, Munday et al. 2009, Dixson et al. 2010, Ferrari et al. 2011), development, growth and mortality (Baumann et al. 2011), and otolith formation (Checkley et al. 2009).

The effects may be species specific, as some studies have not found evidence for some of these effects (Denman et al. 2011). A very recent study of larval reef fish found that elevated CO_2 interfered with the normal functioning of a key brain neurotransmitter receptor Gamma-Amino Butyric Acid (GABA)-A, resulting in severe behavioral changes that could reduce survival rates (Nilsson et al. 2012). GABA-A is highly conserved across marine fish species. Researchers have expressed concern for highly active pelagic species possessing metabolic features that may make them particularly vulnerable to changes in GABA-A functioning (Nilsson et al. 2012). Overall, evidence suggests that ocean acidification may significantly affect recruitment success and population levels for some marine fish species.

The likely effects of ocean acidification on tuna populations have not been investigated but research is clearly a high priority. Decision makers need timely and appropriate scientific advice for fisheries managers to help them determine if there is a need for adaptation planning.

In October 2010 the Pelagic Fisheries Research Program (PFRP) recognized this need and funded a collaborative study of the impact of ocean acidification on the early life history stages of Pacific yellowfin tuna. The study, led by the Secretariat of the Pacific Community and the IATTC, is investigating the effect of ocean acidification upon sperm motility, fertilization rates, embryonic development, hatching rates, condition, development, and growth and survival in pre- and post-feeding yellowfin larvae. The collaboration includes scientists from the Max Planck Institute of Meteorology (Germany), the Collecte Localisation Satellites (France), the University of Gothenburg (Sweden), and Macquarie University (Australia). As tolerance to ocean acidification has been found to be variable on an individual level in other species, the project later added another component to look at whether genotypes (the genetic makeup) of individual yellowfin larvae vary in their responses to different CO_2 levels. This last investigation is a first step towards determining if ocean acidification causes genetic selection of resistant genotypes in this species.

Achotines Facility

Experimental trials were conducted at the IATTC's Achotines Laboratory, Panama, in October and November of 2011. The facility was inaugurated in 1985 and is one of only a few in the world with the location, equipment, and expertise to conduct investigations of this type. Achotines Bay is located on a section of coastline (Figure 1) where the continental shelf drops rapidly and deep oceanic waters are close to shore, allowing researchers to easily access local tuna populations for either field studies of early development or to obtain yellowfin tuna as captive broodstock. At the lab an in-ground concrete tank holds a broodstock population of yellowfin tuna that have spawned on a near-daily basis since October of 1996, providing a reliable source of eggs and larvae for early life history studies.

Experimental Trials

Experimental trials were grouped into three categories: sperm and fertilization trials, egg and larval trials, and genetics analyses. The egg and larval trials were replicated, with two separate trials run in October and November.

Tank set up and pH control—The experimental setup for the fertilized egg and larval trials consisted of fifteen experimental tanks. Each 840 liter (L) capacity tank was nested inside of an 1100 L tank filled with seawater that

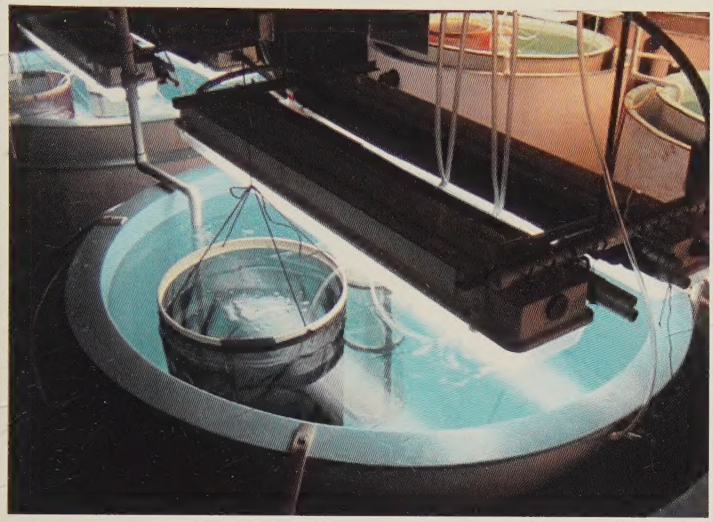

Figure 2. Single experimental tank with nested egg-incubator net. Photo: Donald Bromhead

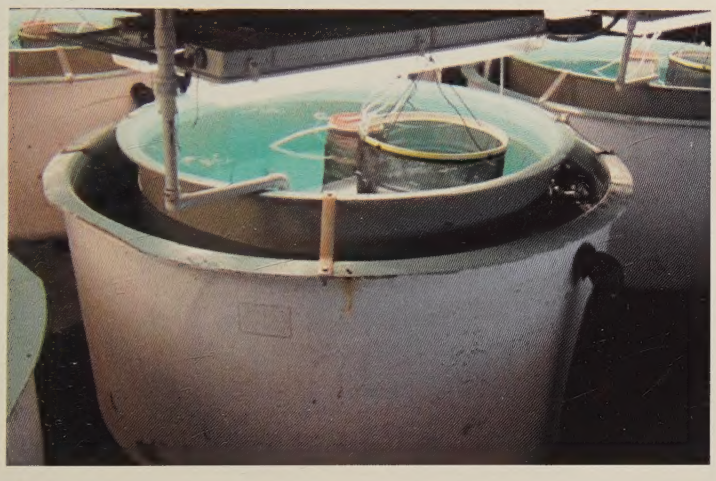

Figure 3. Single experimental tank with nested egg-incubator net. Photo: Donald Bromhead

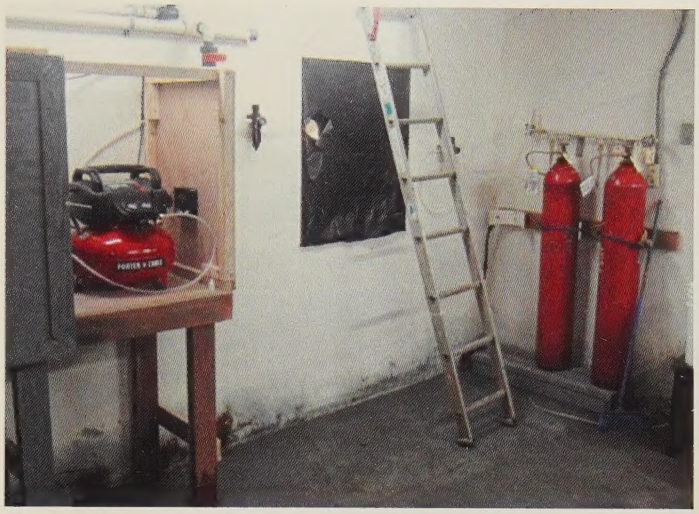

Figure 4. Compressed-air reservoir and CO_2 cylinder bank. Photo: Donald Bromhead

Figure 5. Gas-flow controllers and manifolds used for mixing and distribution of air and CO_2. Photo: Donald Bromhead

acted as a buffer/insulator to stabilize the water temperature in the smaller tank during the trials (Figures 2 and 3). Water flow, lighting, aeration, and turbulence levels were adjusted to set these parameters as uniformly as possible across all tanks.

Five pH treatment levels (modules) were used for the trials with three replicate tanks per module. Treatment levels were based on results from the latest ocean-carbon-cycle models using the Intergovernmental Panel on Climate Change (IPCC) IS92a Scenario (e.g., the Hamburg Ocean Carbon Cycle model, as in Ilyina et al. 2009). The upper limit was set to match the highest average sea-surface pH level observed or predicted in the Pacific between now and 2200 (currently pH 8.2). The middle target was set to match the lowest sea-surface pH observed or predicted in the Pacific for that time period (around 6.9–7.0 by 2200; Caldeira and Wickett 2003). And the low target of pH 6.5 was set at a level well below the lowest predicted pH for that time period. The two remaining treatments were set at intervals between the upper and middle limits, allowing a response curve for the primary larval response variable (mortality) to be modeled and fed into the Spatial Ecosystem and Population Dynamics Model (SEAPODYM; see SEAPODYM below)

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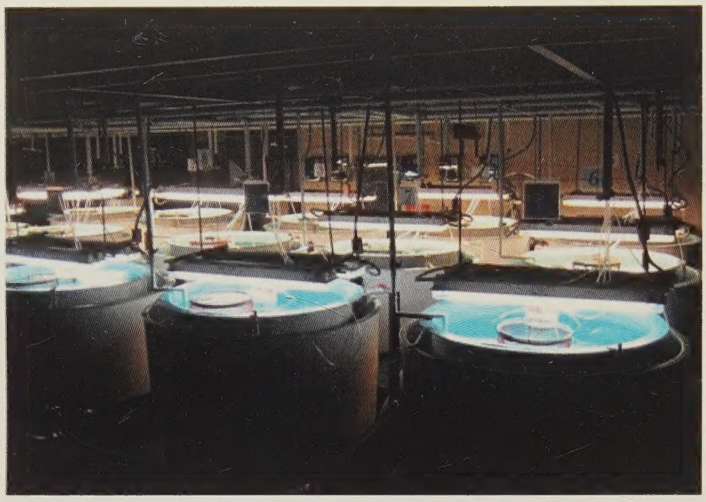

Figure 6. Multiple experimental tanks with nested egg incubators. Photo: Donald Bromhead

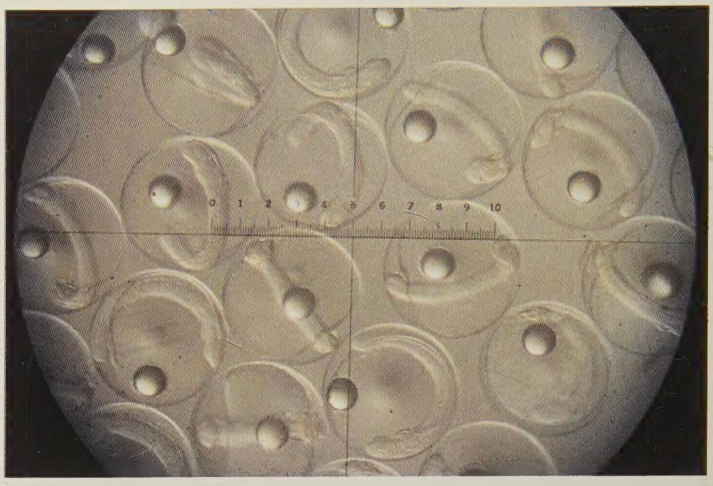

Figure 7. Yellowfin tuna eggs. Photo: University of Miami

Figure 8. Egg-incubator net. Photo: Donald Bromhead

spawning-habitat index. Final target pH levels were 8.2, 7.7, 7.3, 6.9, and 6.5.

The local coastal waters that supply the Achotines Laboratory seawater system were very close to pH 8.2 during the trial period and therefore ambient seawater was used for the high pH level. The four lower treatment levels of seawater pH were maintained by regulation of mixtures of compressed air and CO_2 bubbled through air diffusers in each tank. The use of CO_2 was critical to modifying water chemistry (i.e., increasing carbonic acid, increasing H+, lowering pH) in a manner consistent with CO_2-induced ocean acidification.

In all trials water-quality parameters (pH, temperature, salinity, dissolved oxygen, CO_2, alkalinity) were measured at frequent intervals in each tank. Controlling pH in ocean-acidification experimental systems is a difficult task (Riebesell et al. 2010). For these experiments sophisticated electronic gas-flow controllers were used to precisely control the mix of air and CO_2 supplied to the tanks in each module (Figures 4 and 5). The average pH attained in each module (treatment level) for the first experiment was within 0.15 units of the target pH (and generally much closer). In the second experiment average pH levels in each module varied, at times, by 0.3 units from the target pH.

Fertilized egg and larval trials—The effects of ocean acidification upon mortality, growth, and development of eggs and larvae of yellowfin tuna were tested by rearing larvae from egg stage to first-feeding stage in fifteen tanks (Figure 6) comprising five treatment (pH) levels and three replicate tanks for each treatment (described above). Trials were continuous but effectively comprised three phases: egg phase, yolk-sac larvae phase, and first-feeding larval phase, with sampling regimes differing in each phase. The following describes the methods used in both the October and November trials.

To start the experiment, fertilized eggs (Figure 7) were collected from a daily spawn in the broodstock tank of the Achotines Laboratory and randomly stocked in each of fifteen cylindrical egg-incubation nets nested one per experimental tank (Figure 8). Eggs were stocked in each egg-incubation net at a density of 177 eggs/L and eggs were immediately sampled fresh for weights and measurements. Additional samples of eggs were taken during the incubation period and fixed for subsequent histological examination of tissues.

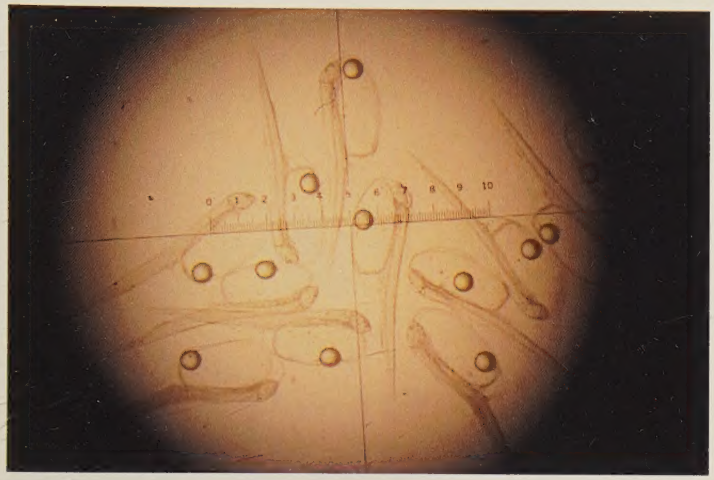

Figure 9. Yellowfin tuna yolk sac larvae. Photo courtesy of University of Miami

Yolk-sac larvae (Figure 9) were then dispersed from the egg-incubation nets into their respective experimental tanks 2 hours (h) after hatching. The yolk-sac phase in yellowfin tuna larvae continues until just prior to pigmentation of the larval eye and development of the mouth (approximately 50–70 h after hatching depending on water temperature). At this point, samples for the estimation of mean larval density and percentage survival were taken at night (when the larvae

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UPCOMING EVENTS

Inter-American Tropical Tuna Commission and Agreement on the International Dolphin Conservation Program Annual Meetings
18–29 June 2012, La Jolla, California, USA
http://www.iattc.org/MeetingsENG.htm

Western Pacific Regional Fishery Management Council 154th Council Meeting
25–28 June 2012, Honolulu, Hawai'i, USA
http://wpcouncil.org/

Western and Central Pacific Fisheries Commission 8th Regular Session of the Scientific Committee
7–15 August 2012, Busan, Korea
http://wcpfc.int/

American Fisheries Society 2012 Annual Meeting
19–23 August 2012, Minneapolis, Minnesota, USA
http://afs2012.org/

Western Pacific Regional Fishery Management Council 155th Council Meeting
29 October–1 November 2012, Honolulu, Hawai'i, USA
http://wpcouncil.org/

Pelagic Fisheries Research Program, Principal Investigators Meeting
November or December (TBD) 2012
East-West Center, Honolulu, Hawai'i, USA
http://www.soest.hawaii.edu/PFRP/

Western and Central Pacific Fisheries Commission 9th Regular Session of the Commission
3–7 December 2012, Manila, Philippines
http://wcpfc.int/

PUBLICATIONS OF NOTE

Geslani, Cheryl, Matthew Loke, Brooks Takenaka, and PingSun Leung. 2012. "Hawaii's Seafood Consumption and its Supply Sources." *SOEST 12-01/JIMAR Contribution 12-379.*

Li, Shichao, and Minling Pan. 2011. "Fishing Opportunities under the Sea Turtle Interaction Caps—A Spatial Bi-Economic Model for the Hawaii-Based Longline Swordfish." *SOEST 11-02/JIMAR Contribution 11-378.*

Figure 10. Marine algae production area. Photo by Donald Bromhead

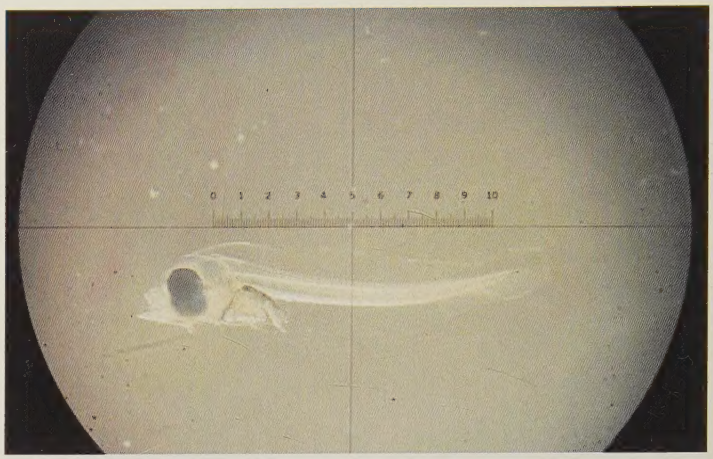

Figure 11. Yellowfin tuna larvae 6 days after hatching. Photo courtesy of University of Miami

do not feed and become uniformly distributed in the darkness) using 2.5 L volume polyvinyl chloride "slurp" samplers. Larvae were also sampled during the yolk-sac phase and fixed for subsequent histological examination of tissue and organ development.

The remaining yolk-sac-stage larvae were maintained in the same experimental tanks until six days after first feeding. Larvae were fed cultured *Brachionus plicatilis* (rotifers) at densities of 3–5/mL. Dense blooms of unicellular algae (500,000–750,000 cells/mL; "green water"; Figure 10) were maintained in each tank to facilitate rearing (IATTC rearing experience has shown that, in laboratory tanks, yellowfin larvae require green water to feed; Margulies, Scholey, et al. 2007).

After five days of feeding (six full days of growth; Figure 11) each tank was slowly drained of water and all surviving larvae were removed by beaker and counted. The percentage of expected survival (adjusted for sample removals; Margulies 1989) was estimated for each tank. Larvae were also sampled at similar intervals and fixed for subsequent histological examination of tissue and organ development (including swim-bladder inflation). Additional larvae were sampled and fixed for subsequent gut analysis (Margulies et al. 2001).

During each phase (egg, yolk-sac, and first-feeding) fresh samples were taken at various intervals from each tank to be measured (total length, notochord length, body depth at pectoral, body depth at vent) and processed for dry-weight determination (Margulies, Suter, et al. 2007). Also during each phase samples were taken from each tank at various intervals to be fixed and stored for subsequent morphometric (size, shape) analyses of the otoliths by high-magnification light microscopy to assess the potential impact of pH on otolith formation (e.g., Checkley et al. 2009).

Genetic Analyses

The genetic component of this research is currently assessing preliminary results for two areas: 1) which parents within the Achotines Laboratory broodstock population contributed to offspring in the next generation for each ocean acidification experiment and 2) whether offspring survival is associated with their genetic composition or level of genetic variation when exposed to different CO_2 scenarios. Work on both objectives is underway using modern genetic techniques such as fluorescent labeling that attaches to specific regions of DNA thus identifying regions of interest. During each experimental trial, samples of at least a hundred eggs or larvae were collected from each of the sample points (above) for later genotype identification and parentage analyses. So far DNA has been extracted from 440 individuals strategically located within the sample points of the first trial and each individual is being analyzed at ten different loci. This aspect of the study will identify the genetic variants best suited to extreme ocean-acidification scenarios along with the genetic modification(s) that have arisen in response to ocean acidification.

Data Analysis

Data collected from the experimental trials described above are still being analyzed. Final results are expected to be reported in the *PFRP Newsletter* later this year.

Future Research: SEAPODYM

It is intended that the results of this project will, in the future, be applied to a SEAPODYM-based evaluation of the expected impact of ocean acidification upon the distribution and abundance of yellowfin tuna in the Pacific Ocean. Physical and biogeochemical conditions influence tuna-population dynamics through changes in spawning conditions, habitat suitability, and distributions of food resources. This results in changes in fish-movement behavior, reproduction, and mortality. Environmental data are used in SEAPODYM to functionally characterize the habitat of the population depending on its thermal, biogeochemical, and forage preferences (Lehodey et al. 2008, 2010). There are three types of habitat indices in the model: 1) thermal, 2) feeding, and 3) spawning. These indices are used to control population-dynamical processes (both spatial and temporal) such as movement to the feeding or spawning grounds, natural mortality, and predation. To simulate the predicted changes in ocean acidity in SEAPODYM it is intended that the spawning-habitat index will be altered, based on the results of these laboratory studies, to include the effect of ocean acidity. The spawning index in the model already accounts for several other mechanisms (e.g., optimal spawning temperature and larvae prey-predator trade off; Lehodey et al. 2008). Additional penalties on the natural mortality of larvae and juvenile fish could be added if these are demonstrated through laboratory experiments. This information will enhance the capacity of regional fisheries management organizations to make more-informed decisions regarding the management of tuna resources, particularly with regard to attaining key sustainability-related objectives.

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Integrating Conventional and Electronic Tagging Data into SEAPODYM

Inna Senina, Francois Royer, Patrick Lehodey, John Hampton, Simon Nicol, Miki Ogura, Hidetada Kiyofuji, and John Sibert

Introduction

Over the past two decades an ever-increasing amount of information on the worldwide movement of individual fish has been collected using conventional and archival-electronic tagging. Methods must now be developed to successfully include the spatial dynamics of fish, reflected by these data, in existing fish-population models. Inclusion of this now-available data will further enable the use of such models in fish-population management analyses and improve the predictive capabilities of these models.

The Eulerian model SEAPODYM (Spatial Ecosystem And POpulations DYnamics Model) was developed to describe the spatio-temporal dynamics of tuna populations under the influence of environmental and fishing pressures (Lehodey et al. 2008). Using maximum-likelihood estimation (MLE) incorporating catch-and-length data within the model significantly improved the agreement between model predictions and actual observations (Senina et al. 2008).

Available fishing data sometimes, however, generated biased parameter estimates and did not always allow estimating all model parameters. Such problems may be created by weak or absent signals caused by poor spatial and/or temporal coverage of fishing effort. Conventional- and archival-electronic-tagging data, unrestricted by such limitations, should provide important additional information and improve parameter estimates—especially those identifying movement and feeding habitat—within the MLE framework.

However including Lagrangian individual movements within a Eulerian model is not a straightforward task. The inclusion of observations derived from either conventional or electronic tags within the population model poses two general problems: 1) explicit modeling of the tagged population implies adding more equations and hence increases computational load and 2) given the sparse nature of such data, many combinations of regions and time periods will be void of individual locations. This is because either they were simply not subject to a tagging initiative or they were not visited by tagged fish. The presence or absence of tagged fish in a given region at a given time is, by itself, a poor indicator of local biomass. Additional problems arise from different spatial and temporal scales described by the population models and the tagging data (combining these data usually requires arguably arbitrary interpolations).

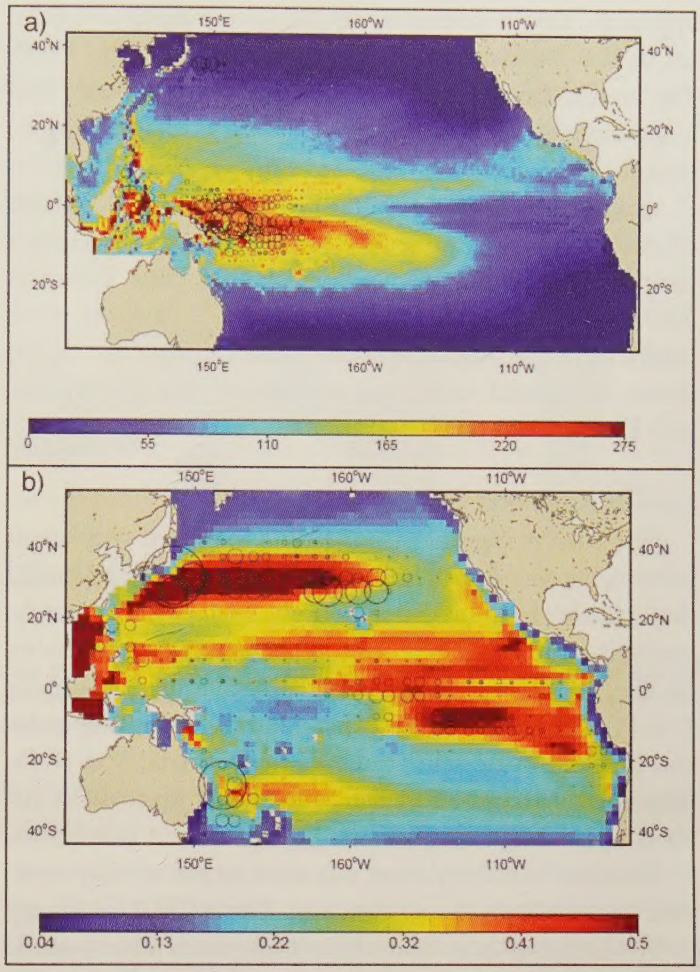

Figure 1. a) Predicted mean annual production (i.e., recruitment, in number/km²/year) of Pacific skipjack and total-annual-catch distribution. Note that diameter of the circles shown are proportional to the total catch in metric tons in a 1° x 1° cell. b) Predicted distribution of Pacific swordfish density (number/km²) and total catch (number of fish caught in 5° x 5° cell). Both solutions are the result of using the MLE approach with CPUE and length-frequencies data.

The Pelagic Fisheries Research Program funded research to compare the feasibility of different approaches to integrating tagging data into SEAPODYM population dynamics. Previous studies, particularly a one-year project funded by the Large Pelagic Research Center (www.tunalab.org), tested two different approaches to incorporating tagging data into a simplified one-cohort version of SEAPODYM. The first

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approach used a conventional tag-release-recapture dataset in the Eulerian-model framework (Sibert et al. 1999). The second imported SEAPODYM's movement rates into a Lagrangian model and estimated the best track using an unscented Kalman filter (Harvey 1990).

A third approach currently being investigated consists of estimating the intermediate variables, such as the space/time vector field of movement (e.g., Preisler 2004, Brillinger 2007) or the probability of fish presence (Thygesen et al. 2009), from the tagging datasets. These can then be used to derive the habitat index and incorporate this information into SEAPODYM predictions.

Current Parameter Estimation in SEAPODYM

The current parameter-estimation approach consists of minimizing a cost function (i.e., a log-negative likelihood) that includes both predicted and observed catch or "catch-per-unit-effort" (CPUE) and relative-length frequencies on the original resolution. Original resolutions are usually 1° x 1° (latitude x longitude, here and following) for pole-and-line and purse-seine catch-and-effort data, 5° x 5° for long-line catch-and-effort data, and 5° x 5° up to 10° x 20° for sampled-length frequencies.

Backward differentiation was used to analytically compute the gradient-of-cost function. The AUTODIF library (a C++ language extension which implements reverse-mode automatic differentiation) provides a function minimizer and a very convenient matrix-manipulation framework. Good accuracy and reasonable computational cost of minimization is achieved with analytical derivatives implemented manually using the adjoint technique.

SEAPODYM, using the MLE approach, has previously been applied to the populations of Pacific Ocean swordfish and four tunas (skipjack, yellowfin, bigeye, and South Pacific albacore). Results were validated using fisheries data not included in the fitting procedure. Overall, for all case studies, the parameter-estimation method employed allowed significant improvement of the model's predictive skills. Model predictions were then used to analyze and quantify the spatial dynamics of tuna species and to test various management scenarios. Figure 1 illustrates two contrasting examples of average spatial distributions of Pacific skipjack and swordfish populations predicted by SEAPODYM.

While conducting analyses using different fisheries datasets and different oceanic forcings, however, problems were identified with the estimation of some model parameters. Problematic parameters were consistently the natural mortality rates of juvenile cohorts, width of the preferred temperature range, tolerance to low concentrations of dissolved oxygen, spatial extension of spawning habitat (as a result of the larvae prey-predator trade-off mechanism), or random movement (diffusion) rates for the species.

As noted above, difficulty in estimating these parameters can be attributed to absent, weak, or misleading signals in the fishing data. Misleading properties of fishing data include changes in fishing practices or target species depending on geographical location within a single fishery. For instance, data from a fishery operating only seasonally provide no valuable information to the function minimizer about the seasonal variability of the local population abundance and its migration pattern.

For fisheries that change their targeted fish, splitting the data into subsets helps improving the function minimization by allowing different selectivity and catchability parameters. When reliable information concerning fishing practices is not available then removing such doubtful data seems to be the best solution.

The task then becomes that of filling in the gaps in the available spatial and temporal information. By integrating conventional- and archival-electronic-tagging data with SEAPODYM habitat-based population dynamics and merging them with fishing data in the data-assimilation framework the parameter estimation will be strongly improved.

Methods of integrating tagging data

Release-recapture data—Considerable efforts have, for decades, been dedicated to the conventional tagging of tuna in the Pacific Ocean area (Figure 2). The Secretariat of the Pacific Community (SPC), in particular, has conducted several large tagging experiments. Since the 1980s they have tagged and released several hundred thousand fish, mainly skipjack and yellowfin tunas, in the western and central Pacific region. The most-current tagging experiment by SPC deployed 166,311 conventional tags on skipjack tuna in the western central equatorial region over the last five years with 26,460 tagged fish recaptured to date (additional information available at http://www.spc.int/tagging/en). The new data should provide an interesting comparison with that of prior tagging experiments conducted in the 1980s and 90s when fishing pressure was significantly less than it is now.

The Inter-American Tropical Tuna Commission and the Japanese Fisheries Agency have been also very active in tuna

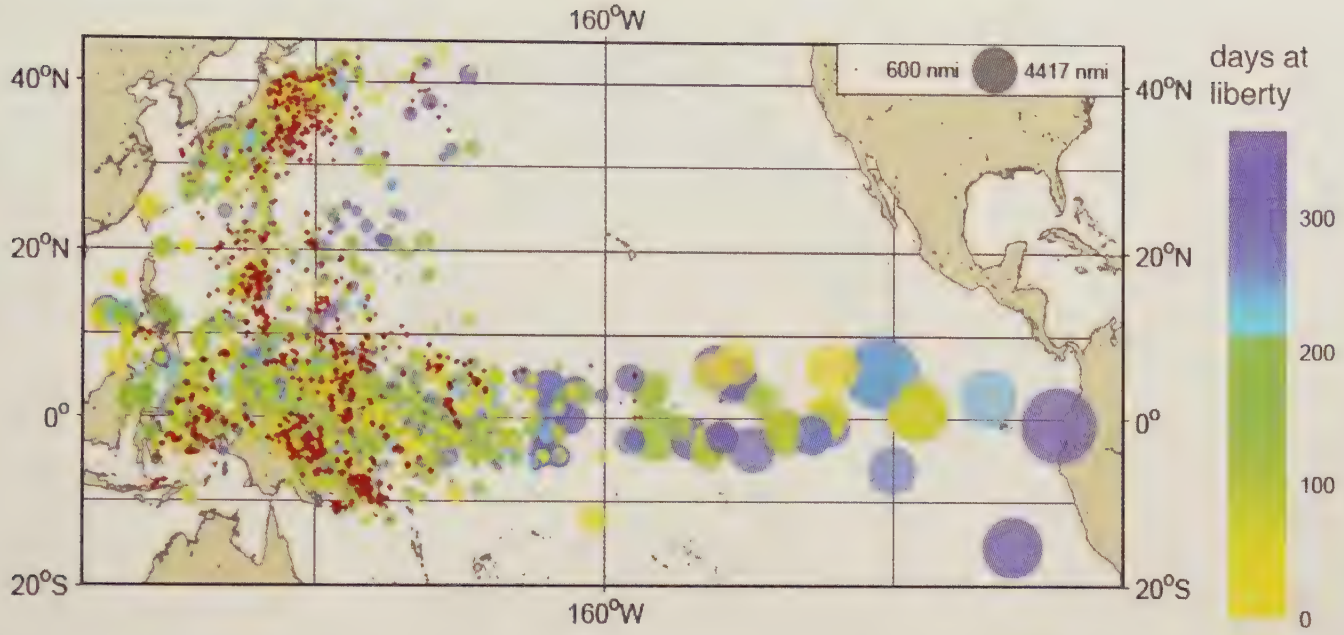

Figure 2. Conventional tagging dataset for 1986–2010, provided for the current study by the Secretariat of the Pacific Community and by the National Research Institute of Far Seas Fisheries. The red marks show the locations of releases; each filled circle corresponds to recapture event. The color of the circle indicates the time at liberty and its radius is proportional to the straight-line distance between release and recapture points.

tagging, in the eastern and north-west Pacific respectively. Their efforts are providing key information on the dynamics of stocks at whole-basin scale and exploring the interactions, particularly under the influence of the El Niño/Southern Oscillation, between these different oceanic regions.

The first approach developed by this project to use tag-release-recapture data within SEAPODYM's Eulerian model is similar to the one earlier developed by Sibert et al. (1999). The tagging dataset is divided, by the size of the tagged fish, into several cohorts. Following the same modeling approach as used in the full-population model of SEAPODYM, a set of advection-diffusion-reaction equations is solved, with either open or closed boundaries, using the observed number of released individuals as initial conditions. The number of tag returns is predicted using the fishing-effort data and fitted to the observed returns through the minimization of the negative log-likelihood function.

A first set of experiments with conventional tagging data was done for skipjack tuna using the Skipjack Survey and Assessment Programme 1977–1982 dataset and a single-cohort version of SEAPODYM. Encouraging results were achieved with a good fit to the data (see Figure 3) for a limited number of parameters (habitat temperature, movement rates, natural mortality rate, and a constant catchability per fishery).

While this approach is relatively simple in concept, combining it with the SEAPODYM age-structured population requires augmenting the model-state vector describing the density of cohorts by a possibly large number of variables. Recent developments in modeling code have, however, allowed decreasing the memory required for intermediate variables by 15 percent. Additionally the latest version of the AUTODIF library allows allocating the more-than-4Gb of processing memory necessary for computing the cost-function-gradient for a fine-resolution spatial model with many variables (e.g., SEAPODYM). Both improvements balance the increased computational demands needed to make this method feasible for the integration of tagging data into full-population models.

Conventional- and archival-electronic-tagging data— The method above developed for utilizing conventional tagging can be employed also for archival-electronic-tagging data. This requires assuming that "recaptures" (or tag "returns") occur at every time step of the model at the tag-recorded positions but do not result in the mortality of "recaptured" fish as does conventional tagging. The predicted number of tag "returns" is then computed for the immediate vicinity of a specific location and compared with the number of observed tag "returns" for this location. The problem

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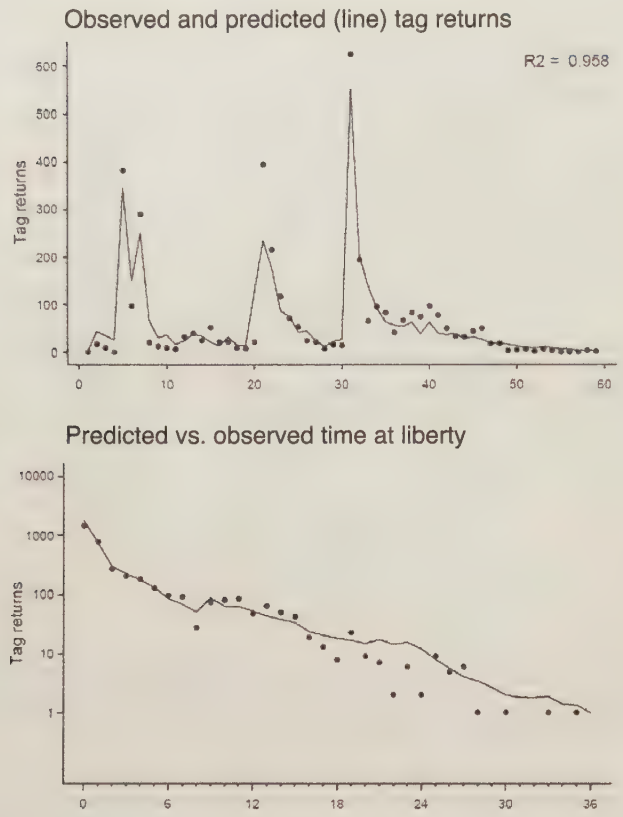

Figure 3. The fit achieved using an MLE approach with the habitat-based one-cohort Eulerian model and tag-release-recapture data from the Skipjack Survey and Assessment Programme.

with this method is that individual movements cannot be followed using a Eulerian model—only instantaneous-tag-density distributions can be analyzed.

An alternative approach combines both conventional and archival datasets. Probability-density distributions are built from the tagging datasets, both conventional and archival, and these intermediary results are incorporated into SEAPODYM's likelihood formulation. Given the relatively low cost of deployment for conventional tagging, this approach may be particularly profitable for such tagging data.

Conventional-tagging datasets contain an order of magnitude more replicates (~100,000) than do archival-electronic-tagging datasets (~10,000). However the information gathered per individual (a single pair of location points and, sometimes, body length) is much more limited. The "Hidden Markov Model," previously successfully applied to movement modeling of flat fish in the Northern Sea (Thygesen et al. 2009), appeared well adapted to this case. The lack of intermediary observations with conventional tagging (as opposed to archival-electronic tagging) and the complex boundaries of the studied region (e.g., including Micronesia and Papua New Guinea) require explicitly accounting for boundaries and correctly propagating uncertainty throughout a complex domain. This problem is more limited in data-intensive scenarios (such as tracking Argos- or GPS-equipped marine animals) where standard Kalman-based solutions are adequate. Thygesen et al. (2009) offers an excellent description of the Hidden Markov Model and its application to fish tracking.

For conventional tags no observation sequence is available. Hence the use of an update step, as described by Thygesen, is eliminated in our approach. Instead an Alternate-Direction-Implicit method is used to solve for the diffusion of probability of presence over the grid with zero-flux boundary conditions both at the limits of the domain and along coastlines. This enforces the absence of possible movement on land without leaking any probability mass. Final probability distributions are then computed, following Briers et al. (2010), using an application of the two-filter smoother formula.

A conventionally tagged fish released (see Figure 4) at 11.483° N, 117.7167° E (green dot), and recaptured (time at liberty was 92 days) at 2.843° S, 145.64° E (red triangle), was chosen as an illustration case. The region of study is bounded by 25.0° S and 25.0° N and 105° E and 175° E. No flux is assumed at these borders. The land mask was inferred from the ETOPO2 product (http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html), re-gridded at a ground resolution of 9 km. A coefficient of diffusion of 1,000 km^2 /day was assumed, and a forward pass (from the time of release to the time of recapture) was applied, followed by a backward pass (from the time of recapture to the time of release). Smoothing was applied using the two-filter smoother (Briers et al. 2010). Figure 4 shows the estimated distribution of the probability density summed over the whole period between release and recapture events.

Future effort is planned to extend this approach to the entire available conventional-tagging database and then use the outputs as intermediate results to infer maps of mean habitats to help refine the parameters found in SEAPODYM. The weakness of this approach is the sensitivity of the constructed variables to the release locations. Dependence on movement-model parameters may interfere with implementation of this approach during the final phase of the study.

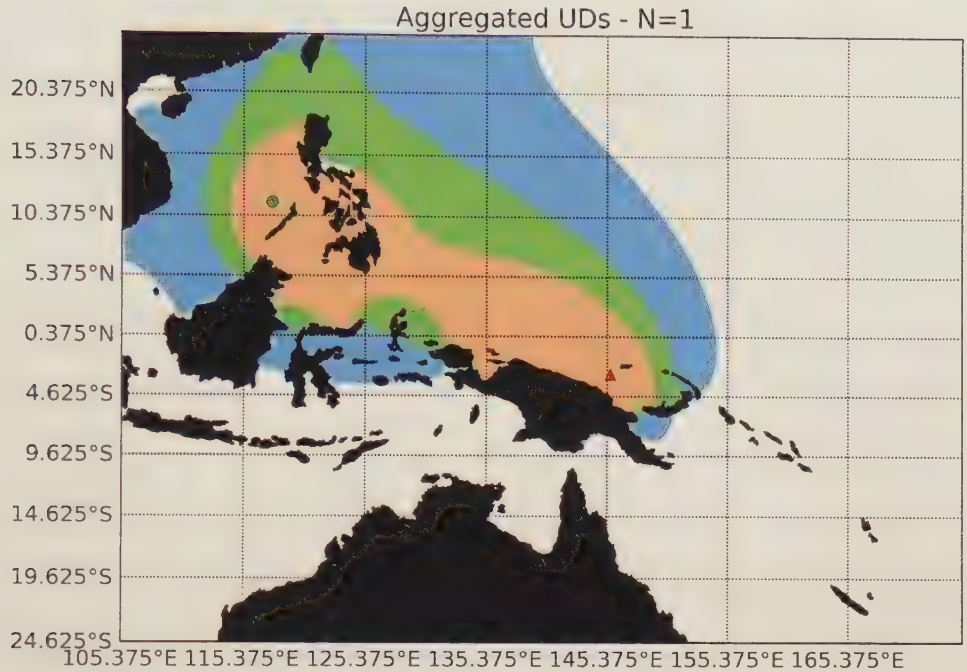

Figure 4. Utilization Distribution computed for a fish fitted with a conventional tag released at 11.483° N, 117.7167° E (green dot), and recaptured 2.843° S, 145.64° E (red triangle). Time at liberty was 92 days. Probability surfaces were computed assuming a coefficient of diffusion of 1,000 km^2 /day. The pink, green, and blue colors indicate the 50%, 75%, and 95% confidence intervals, respectively.

Conclusion

Both modeling approaches proposed here to integrate archival-electronic-tagging data are intended to describe the characteristics of individual fish movements as well as estimate habitat parameters for the tagged-fish sample. However neither allows estimating the parameters governing overall population dynamics. There remains a need to combine both fishing and tagging data within the population model.

Effort is currently focused on extending the one-cohort version of release-recapture approach to the full population model. Sequential assimilation of tagged cohorts of fish over the time series of the simulation is planned. Modeling code will be tested using twin experiments requiring the creation of pseudo datasets. Both conventional- and archival-electronic-tagging data will be used and the model will be run in optimization mode to test if the original solution used to create the artificial tagging data can be retrieved. These datasets will be created using the parameters previously estimated solely on the basis of fishing data.

An interesting by-product of the test phase associated with the development of the new SEAPODYM version should be a Tagging System Simulation Experiment (TSSE), applied to tagging data, equivalent of the Observing System Simulation Experiment (OSSE).

OSSEs are studies routinely used in physical oceanography to optimize sampling strategies, i.e., where to release observational platforms to retrieve the best information to generate, constrain, and validate ocean-circulation models. OSSEs provide advantages including easy control of the experiments and precise knowledge of the true data properties and errors. Given the costs of both conventional- and archival-electronic-tagging experiments the tagging equivalent of such a tool would certainly be useful in testing various ocean-scale tagging scenarios.

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PFRP-supported Research Underlies Conservation Measures for the Oceanic Whitetip Shark

William A. Walsh and Keith A. Bigelow

Introduction

The eighth annual meeting of the Western and Central Pacific Fisheries Commission (WCPFC) held 26–30 March 2012 in Tumon, Guam, considered and then passed by consensus a Conservation and Management Measure (CMM) for oceanic whitetip shark *Carcharhinus longimanus.* This species (Figure 1) is a large, oceanic, pelagic shark circumglobally distributed in tropical and semitropical waters. It is an apex predator traditionally considered to be among the most abundant of oceanic pelagic sharks. However, in many locales, catch rates for this species appear to be declining.

The CMM was sponsored by the United States and adopted by consensus by all commission members. The scientific information that underlay the agreement and resulting conservation measure was generated primarily by Dr. Shelley C. Clarke, formerly of the Oceanic Fisheries Programme of the Secretariat of the Pacific Community (SPC/OFP) located in Noumea, New Caledonia, and Dr. William A. Walsh, for over fourteen years a Pelagic Fisheries Research Program (PFRP) researcher located at the National Oceanic

Figure 1. Oceanic whitetip shark *Carcharhinus longimanus*. Photo: NOAA Fisheries Pacific Islands Regional Observer Program.

and Atmospheric Administration/Pacific Islands Fisheries Science Center (NOAA/PIFSC). Clarke and Walsh were the lead authors of a series of working papers documenting large declines in standardized oceanic whitetip shark catch rates over the last two decades in widely separated regions of the Pacific Ocean.

Research

Walsh's research, partially funded by PFRP, was made possible by an invitation extended by Dr. John Hampton, chief of the SPC/OFP, in January 2011. This allowed Walsh to spend April 2011 at the SPC analyzing a sixteen-year time series of catch and catch-rate data for oceanic whitetip sharks that had been collected by the NOAA Fisheries Pacific Islands Regional Observer Program.

The analyses entailed fitting generalized linear models of catch and catch-rate data from observed longline sets. The nominal catch per unit effort (CPUE) trend and two standardized trends (Figure 2) all indicated that oceanic whitetip sharks had undergone a significant decline in this fishery during the sixteen-year study period. (The decline in the Hawai'i-based pelagic longline fishery from 1995 through 2010 was ca. 90%.)

Working papers that described these results and those produced by Clarke and her colleagues were submitted to the 7th Regular Session of the Scientific Committee (SC) of the WCPFC in August 2011. Advice from the SC supported a reduction in fishing mortality on oceanic whitetip sharks and recommended that, on the basis of existing information, WCPFC 2012 meeting consider mitigation measures for oceanic whitetip sharks in the convention area.

Mitigation Measures

The adopted WCPFC CMM shall take effect on 1 January 2013 requiring that:

1. Members, cooperating non-members, and participating territories shall prohibit vessels flying their flag and vessels under charter arrangements to the members, cooperating non-members, and participating territories from retaining on board, transshipping, storing on a fishing vessel, or landing any oceanic whitetip shark, in whole or in part, in the fisheries covered by the Convention.

2. Members, cooperating non-members, and participating territories shall require all vessels flying their flag and vessels under charter arrangements to the members, cooperating non-members, and participating territories to release

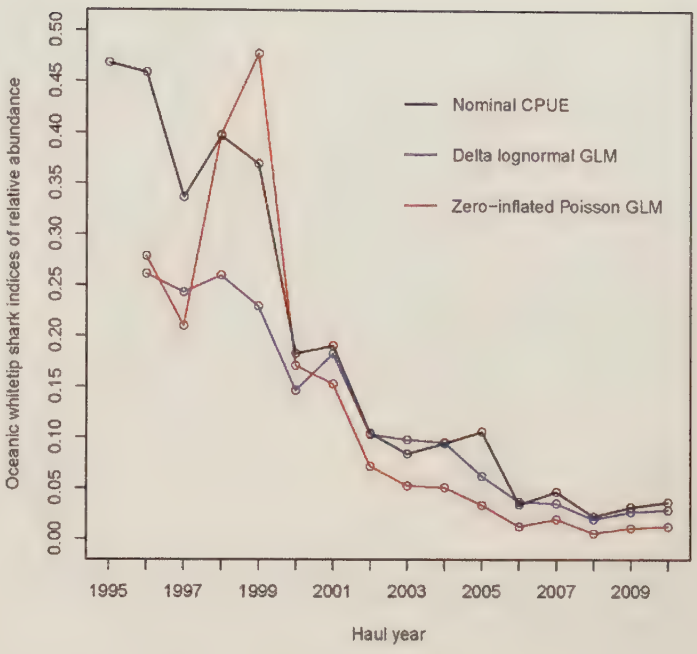

Figure 2. Nominal catch per unit effort (black trace), an index of relative abundance fitted by the delta lognormal method (blue trace), and an index of relative abundance fitted by the zero-inflated Poisson method, for oceanic whitetip shark *Carcharhinus longimanus* in the Hawai'i-based pelagic longline fishery 1995–2010. All data were collected by the NOAA Fisheries Pacific Islands Regional Observer Program.

any oceanic whitetip shark that is caught as soon as possible after the shark is brought alongside the vessel, and to do so in a manner that results in as little harm to the shark as possible.

3. Members, cooperating non-members, and participating territories shall estimate, through data collected from observer programs and other means, the number of releases of oceanic whitetip shark, including the status upon release (dead or alive), and report this information to the WCPFC in Part 1 of their Annual Reports.

4. The Commission shall consider the special needs of Small Island Developing States and Territories, including supplying species identification guides for their fleets and develop guidelines and training for the safe release of sharks.

5. Observers shall be allowed to collect biological samples from oceanic whitetip sharks that are dead on haulback in the WCPFC provided that the samples are part of a research project approved by the Scientific Committee. To gain such approval a detailed document outlining the purpose of the work, number of samples intended to be collected, and the

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spatio-temporal distribution of the sampling effort must be included in the proposal. Annual progress of the work and, upon completion, a final report shall be presented to the Scientific Committee.

The WCPFC CMM is similar to a measure adopted by the Inter-American Tropical Tuna Commission (IATTC) for oceanic whitetip shark in July 2011. As such, both regional fishery management organizations (RFMOs) in the Pacific Ocean now have consistent conservation measures for this widely distributed, ecologically important, shark species that has undergone a significant decline in relative abundance.

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How Much Seafood Does Hawai'i Consume?

Matthew Loke, Cheryl Geslani, Brooks Takenaka, and PingSun Leung

Introduction

Seafood is easily recognized as an important staple in the diets of Hawai'i residents. Living in the only state in the U.S. surrounded by ocean, Hawai'i residents have always taken their seafood seriously. How much seafood is actually consumed by Hawai'i residents, and how does this compare with seafood consumption for all U.S. residents?

On an annual per capita basis, in 2005 Hawai'i residents spent more than double the amount spent by all U.S. residents on seafood consumed at home (for details on this and following comments, see Table 1; Figures 1–2). The amount is also nearly double the $53.46 spent by residents of the U.S. western region. Table 1 compares the annual per capita seafood expenditure of Hawai'i residents with that of all U.S. residents for consumption at home, and at food-service establishments separately, and combined. Hawai'i residents also spent nearly double the proportion spent by all U.S. residents of their total annual food expenditure on seafood.

Table 1. Hawai'i vs. All U.S. Per Capita Seafood Expenditure by Consumption Site (2005)

Consumption Site	Hawai'i	All U.S.
At Home	$104.29	$45.20
Food-Service Establishments	$226.39	$98.12
Sub-Total	$330.68	$143.32
Total Food	$2,888.93	$2,372.40
Proportion of Seafood	11.4%	6.0%

Source: Loke et al. (2012)

Apparent Seafood Consumption

The apparent-consumption approach in our analysis is adopted from the United Nations Food and Agriculture Organization's disappearance model. It is defined as seafood production plus imports minus exports. Seafood production is further defined as the sum of commercial landings, aquaculture production, and non-commercial catch.[1] Table 2 shows the estimates of Hawai'i total apparent seafood consumption, and the various components as an annual average for the ten-year period 2000–2009. The estimates, measured in edible pounds, are expressed in the various components of seafood production, imports, and exports.

Excluding non-commercial catch, the apparent seafood consumption on an annual average in Hawai'i is 38.9 million edible pounds. With the inclusion of non-commercial catch, the estimate increases to 50.4 million edible pounds. On a per capita basis,[2] the seafood consumption on an annual average in Hawai'i is 29 edible pounds without including non-commercial catch, and 37 edible pounds with the inclusion of non-commercial catch. The eight-pound per

[1] Non-commercial catch includes sport and recreational fishing but excludes illegal or unreported fishing.

[2] The total estimate is divided by the de facto population in Hawai'i which takes into consideration military personnel stationed in and tourists visiting the state.

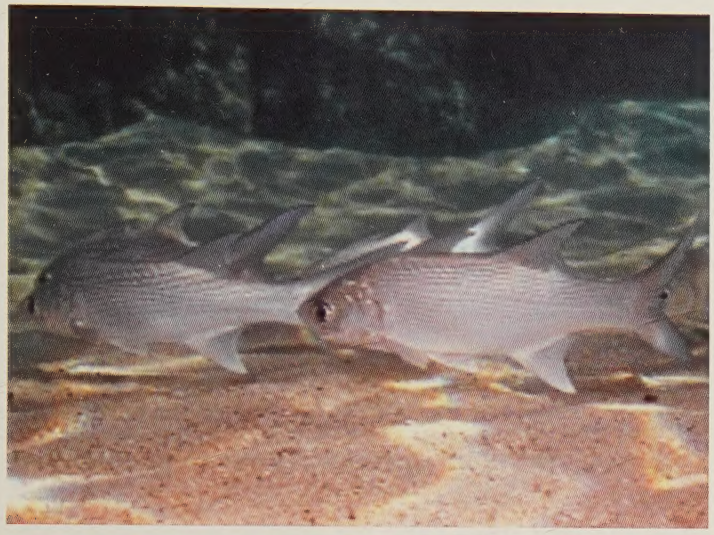

Figure 1. Hawaiian *moi* (Pacific threadfin, *Polydactylus sexfilis*) is a local favorite. (Photo: Keoki Stender/Marinelife Photography)

Figure 2. *Sashimi* platter with an assortment of fresh seafood available in local markets (Photo: John Kaneko/Hawaii Seafood Council)

capita differential shows the significant contribution of non-commercial catch to Hawai'i's seafood-supply chain.

Historical Comparison

The first study of Hawai'i's apparent seafood consumption (measured in edible pounds), covering the eight years from 1970 to 1977, found that the apparent seafood consumption per capita in Hawai'i was 1.7 times higher than that in all U.S. In Table 3, the estimate of the current apparent seafood consumption per capita in Hawai'i is only marginally higher, at 1.8 times, than that in all U.S. based on average annual consumption from 2000 to 2009.

Seafood Imports

As shown in Table 2, the majority of Hawai'i's seafood is imported. While the countries of origin for foreign transshipments via the continental U.S. are not documented, direct Hawai'i imports by country of origin are well recorded. For 2010 the total Hawai'i import of edible seafood products was 17.7 million pounds, valued at $36.3 million.[3] The five leading direct-import sources for Hawai'i's seafood by edible pounds, as reported by the United States Department of Agriculture (USDA) Foreign Agricultural

[3] These figures from USDA-FAS, GATS Online Database include edible products only and exclude ornamental items such as *koi*, carp, etc.

Table 2. Hawai'i Total and Per Capita Apparent Seafood Consumption, Edible Pounds, Annual Average for 2000–2009

	Hawai'i Production (1,000 pounds)		+	Imports (1,000 pounds)		-	Exports (1,000 pounds)		=	Consumption	
	Commercial Landings*	Non-Commercial		U.S.	Foreign		U.S.	Foreign		Total (1,000 pounds)	Per Capita (pounds)
Commercial Consumption	18,108			2,467	22,075		3,128	599		38,922	28.5
% Total	46.5%			6.3%	56.7%		-8.0%	-1.5%		100.0%	
Commercial + Non-Commercial Consumption	18,108	11,465		2,467	22,075		3,128	599		50,387	36.9
% Total	35.9%	22.8%		4.9%	43.8%		-6.2%	-1.2%		100.0%	

Note: *Includes aquaculture production.

Source: Loke et al. (2012).

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Table 3. Hawai'i vs. All U.S., 1970s and 2000s: Per Capita Seafood Consumption, Edible Pounds

	1970–1977[1]			2000–2009[2]		
	Hawai'i	All U.S.	Hawai'i:All U.S.	Hawai'i	All U.S.	Hawai'i:All U.S.
Consumption	20.9	12.4	1.7:1	28.5	15.92	1.8:1
Change	-	-	-	36.4%	28.4%	5.9%

[1] Figures for 1970–1977 from Hudgins (1980).

[2] Data is average from 2000 to 2009 of all U.S. per capita use of commercial fish and shellfish from NOAA-NMFS (2001–2010).

Source: Geslani et al. (2012)

Table 4. Top Ten Hawai'i Seafood-Import Sources by Country of Origin, Volume, and Value, 2010

#	Origin	(1,000 pounds)	($000)
1	Taiwan	4,532	3,380
2	Japan	1,963	4,934
3	Philippines	1,929	2,894
4	New Zealand	1,784	4,198
5	China	1,395	3,711
6	Marshall Islands	1,387	2,227
7	Thailand	1,259	2,446
8	Canada	1,068	3,614
9	Indonesia	633	1,691
10	Micronesia	559	1,291

Source: Loke et al. (2012).

Service (FAS) Global Agricultural Trade System (GATS) Online Database, were Taiwan, Japan, the Philippines, New Zealand, and China. When expressed in dollar value, the top five seafood-import sources by country of origin were Japan, New Zealand, China, Canada, and Taiwan. Table 4 lists the top ten Hawai'i seafood-import sources by country of origin in 2010 in terms of edible pounds, and corresponding dollar value.

Conclusion

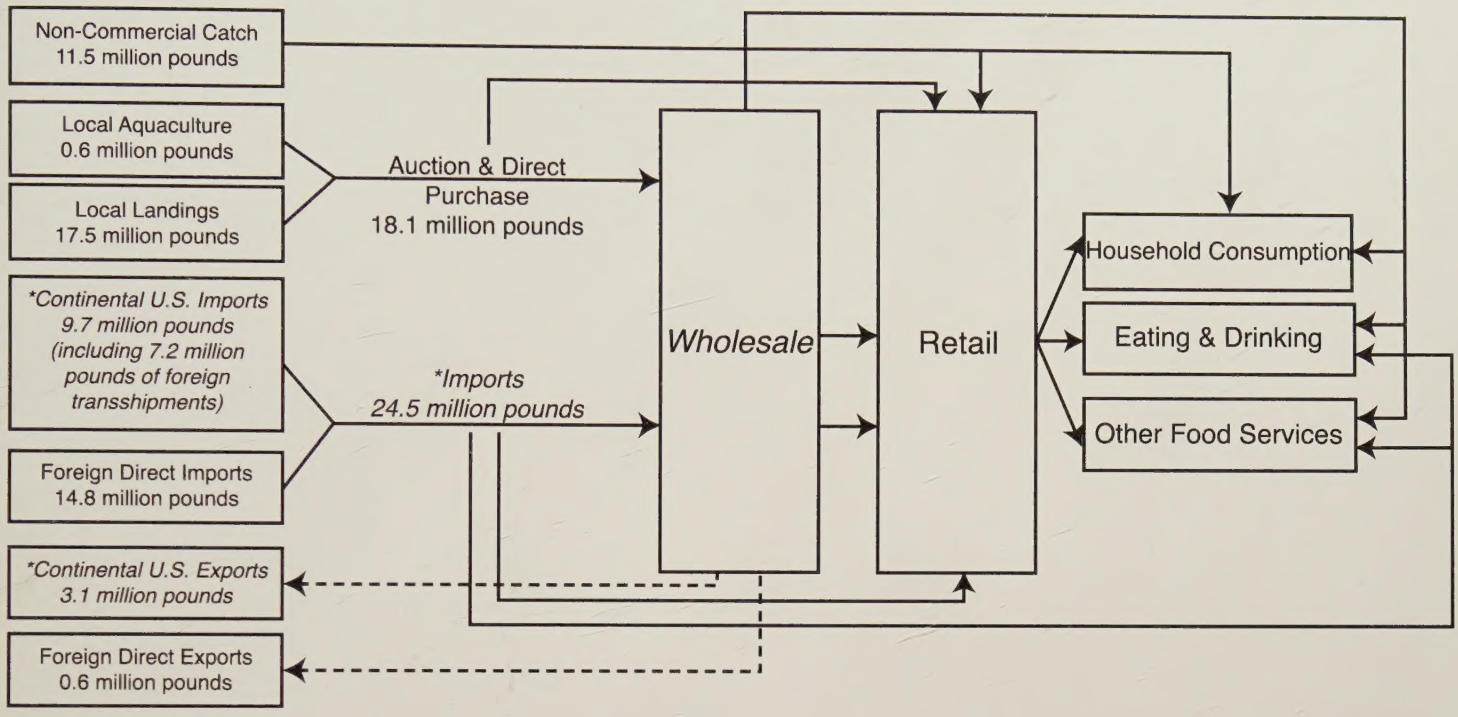
This study was intended to assess multiple dimensions of seafood activity—including expenditures, supply sources, consumption per capita, and forms of seafood consumed—in Hawai'i. This study documents that Hawai'i residents consume significantly more seafood per capita from all sources than that consumed by all U.S. residents (roughly 29 edible pounds vs. 16 edible pounds). Additionally, non-commercial catch contributes a significant amount, estimated at 39 percent of total seafood production in Hawai'i (equivalent to roughly 8 edible pounds per capita), to the Hawai'i supply.

Interestingly, while per capita seafood consumption in Hawai'i has increased over time (36.4 percent between 1970–1977 and 2000–2009), the ratio of seafood consumption between Hawai'i residents, and all U.S. residents has not changed significantly over the same period (ratios of 1.7:1 in 1970–1977 and 1.8:1 in 2000–2009), as all U.S. residents have similarly increased their consumption of seafood. However, this study identified noteworthy contrasts in the variety and form of seafood eaten by each population. Hawai'i residents consume more fresh and frozen finfish whereas all U.S. residents consume more shellfish and processed seafood.

Figure 3 indicates a plan for continuing research in the seafood value chain in Hawai'i. It will be important to continue to measure the seafood supply flowing from the wholesale sector to eating and drinking establishments (restaurants), other food-service establishments (food catering) and, (usually but not always, through commercial retail, to) households. Similarly, it will be useful to continue to measure import flows directly to eating and drinking establishments, other food-service establishments, and commercial retail.

Hawai'i residents are heavily dependent on seafood imports, receiving 57 percent of their commercial seafood supply from foreign sources, and another 6 percent from the continental U.S. Imports account for 49 percent of the total seafood (including non-commercial catch) consumed in Hawai'i—with 44 percent from foreign countries, and 5 percent from the continental U.S.

As those countries currently exporting seafood to Hawai'i address their own increasing domestic consumer demands for seafood, Hawai'i's ability to continue to rely on foreign seafood imports may be reduced. Factors involved in this potential reduction of Hawai'i's access to imported seafood



Note: **Italicized* components refer to estimates based on multiple sources of information versus an officially published data source.

Figure 3. Hawai'i's Seafood Value Chain, 2000–2009 Average. Flow chart showing seafood volume of local landings, local aquaculture, non-commercial catch, and imports to wholesale, retail, and end-use establishments, as well as export volume to the continental U.S. and foreign countries. Source: Geslani et al. (2012)

include both population, and income growth in exporting countries, continued depletion of ocean resources in exporting countries, and rising cost of transportation. The last factor noted, rising cost of transportation, is largely driven by continuously rising energy costs.

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PFRP

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